UCRL-PRES-221518

Concepts for Reducing Costs of DPSSL Drivers For IFE

Al Erlandson, John Caird, John Murray, Camille Bibeau, Ray Beach, Tony Ladran, and Mary Spaeth

National Ignition Facility Programs Directorate
Lawrence Livermore National Laboratory
Livermore, California USA 94550

2006 HEC DPSSL Workshop
Lawrence Livermore National Laboratory
May 17-19, 2006

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Summary

- DPSSL drivers that are based on current concepts are too expensive for economically-competitive IFE power plants

- Pulse stacking holds promise for reducing DPSSL driver costs

- A laser-pumped laser architecture has advantages

- We plan to evaluate and develop these concepts

Summary

- DPSSL drivers that are based on current concepts are too expensive for economically-competitive IFE power plants

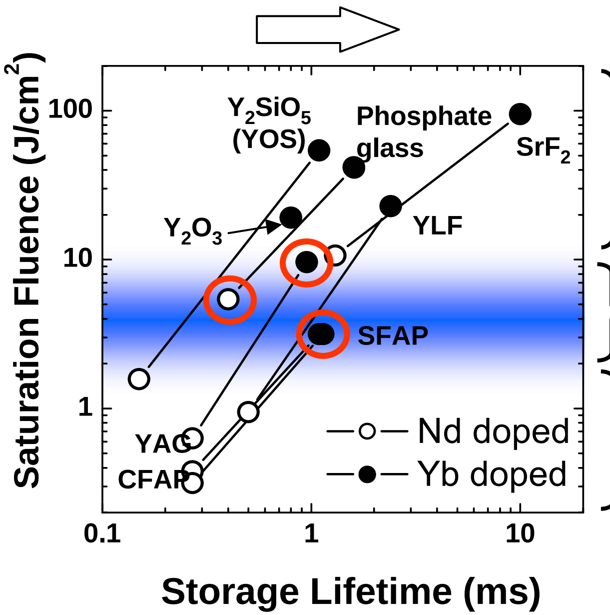
- Pulse stacking holds promise for reducing DPSSL driver costs

- A laser-pumped laser architecture has advantages

- We plan to evaluate and develop these concepts

We evaluated three different gain media having saturation fluences in the “acceptable” range

Reduced diode cost due to increased energy storage time



$\phi_{sat} \propto \tau_{store}$

Large ϕ_{sat} ➔ high fluence needed for efficient extraction in a few passes, high damage risk

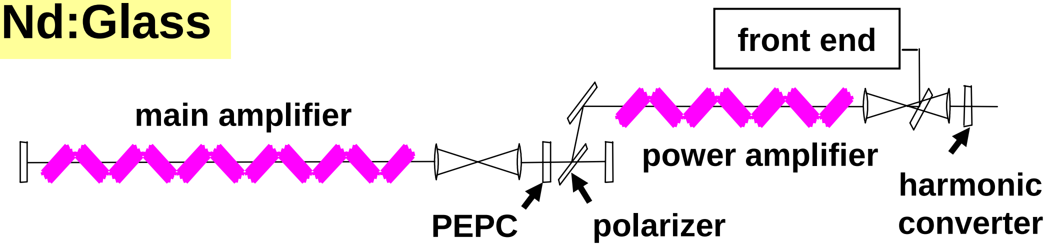
Acceptable range for producing ns pulses

Small τ_{store} ➔ amplified spontaneous emission decay causes excessive stored-energy loss

	Advantages	Disadvantages
Nd:glass	Demonstrated manufacturing	Short storage lifetime, ~ 0.3 ms Poor thermal conductivity
Yb:S-FAP	Long storage lifetime, ~ 1ms	Crystals difficult to grow
Yb:YAG ceramic	Long storage lifetime, ~ 1ms Good prospects for manufacturing	Cryogenic operation (100K)

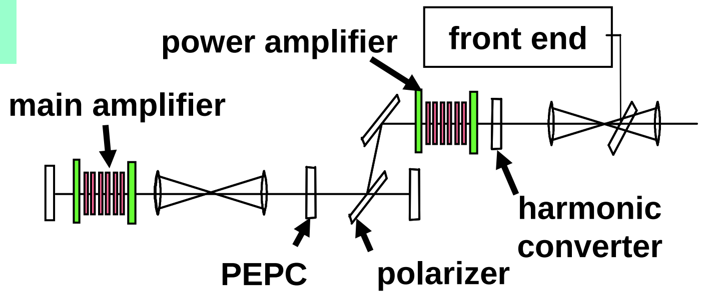
The three IFE system designs used gas-cooled-slab lasers to produce 2.7 MJ at 2ω at 10 Hz

Nd:Glass



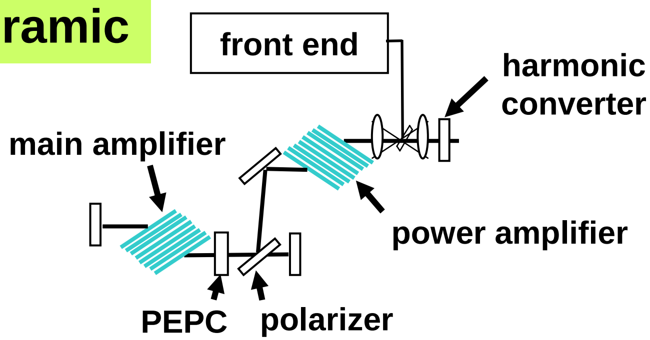
- 40 cm x 40 cm aperture
- 4 beam lines per port
- 192 total beam lines

Yb:S-FAP



- 20 cm x 30 cm aperture
- 16 beam lines per port
- 768 total beam lines

Yb:YAG cryogenic ceramic

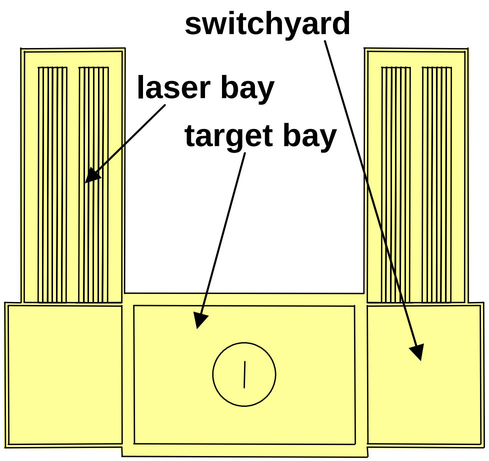


60m

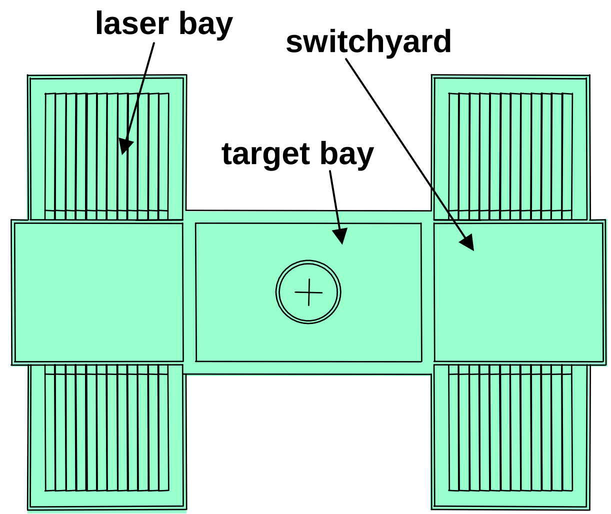
- 40 cm x 40 cm aperture
- 8 beam lines per port
- 384 total beam lines

- All three systems had:
  - 4-passed cavity amplifier
  - 2-passed power amplifier
  - 20% optical-to-optical efficiency

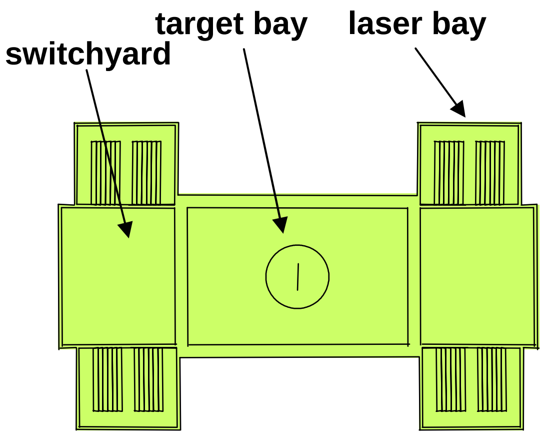
Cryogenic YAG had the smallest “footprint”



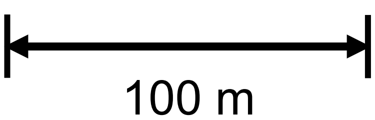
Nd:Glass Facility – 192 beam lines (2x2 bundle)



Yb:SFAP Facility – 768 beam lines (4x4 bundle)



Yb:YAG Facility – 384 beam lines (2x4 bundle)



- 1 GW power plants

Estimated laser-driver costs are > $2B

	Nd:Glass	Yb: S-FAP	Yb:YAG ceramic at 100K
Laser TDC ($B)	2.3	3.3	2.5
Laser TDC per Joule ($/J)	850	1200	925

- 2.7-MJ / 2ω / 10 Hz laser for a 1 GW power plant

- direct-drive target with gain of ~100

- costs for n^{th} power plant, in 2005 $

- NIF design was the starting point

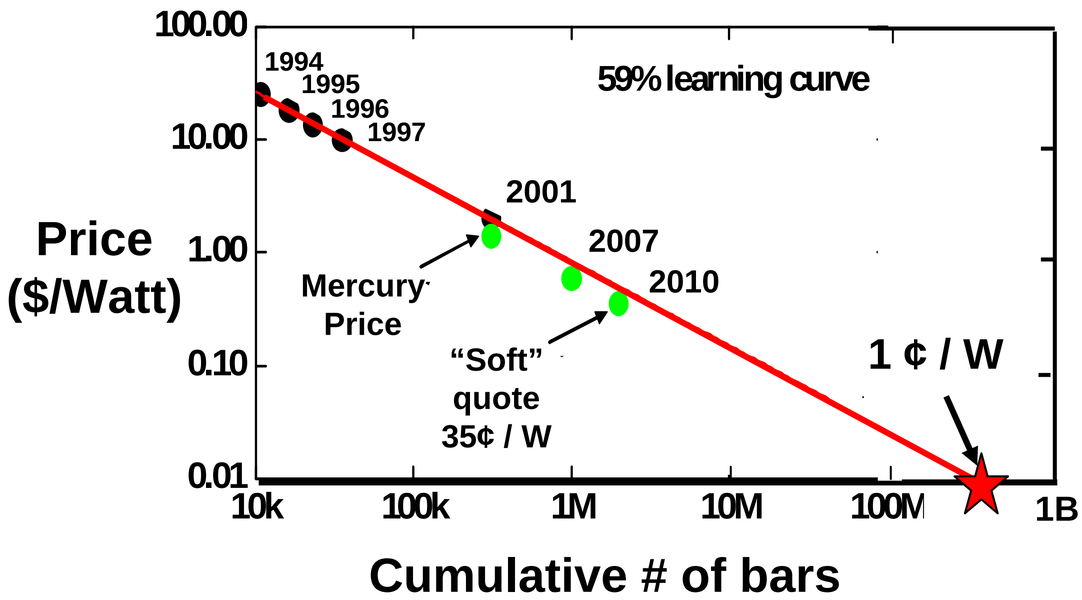
- Laser diodes costs were $0.01 per watt (un-mounted)

- Laser total direct cost (TDC) includes laser equipment, facilities, and the laser building

• Economically-competitive 1GW power plants must cost < ~ $3 – 4 B, so lower driver costs are needed

• Possible pathways to lower driver costs are:
  - advanced targets with higher gain, which require smaller drivers
  - new concepts for laser driver designs

A diode cost of $0.01/Watt was assumed for the IFE laser cost study



Price does not include
- packaging
- power conditioning

Mercury prices:	
- diodes	\$1.30/W
- packaging	\$2.50/W
- power conditioning \$	\$0.54/W
total	\$4.34/W

- Diode cost per Watt has been following a steep learning curve
- 1 ¢ / Watt seems achievable after several power plants have been built
- Relying on industry to provide diodes at a cost of 1 ¢/W poses considerable risk, however

- Packaging is currently highly labor intensive
- Learning curves for packaging and power conditioning are unknown
- Diode efficiency and brightness are likely to increase as a result of DARPA's SHEDS Program (Super High Efficiency Diode Sources)

Summary

- DPSSL drivers that are based on current concepts are too expensive for economically-competitive IFE power plants

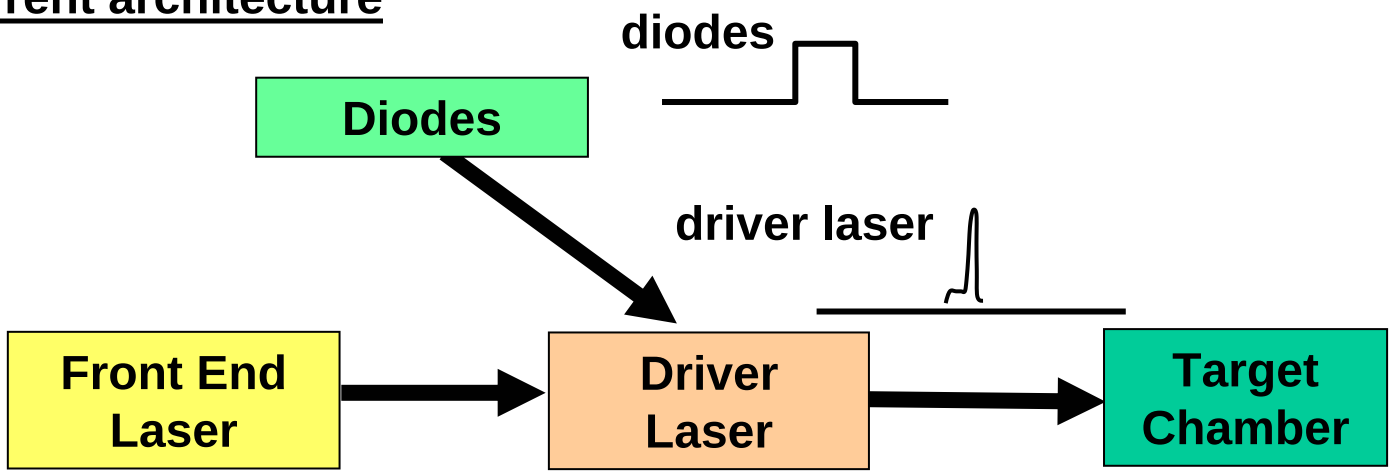
- Pulse stacking holds promise for reducing DPSSL driver costs

- A laser-pumped laser architecture has advantages

- We plan to evaluate and develop these concepts

Current designs use laser components at low repetition rates and low duty cycles

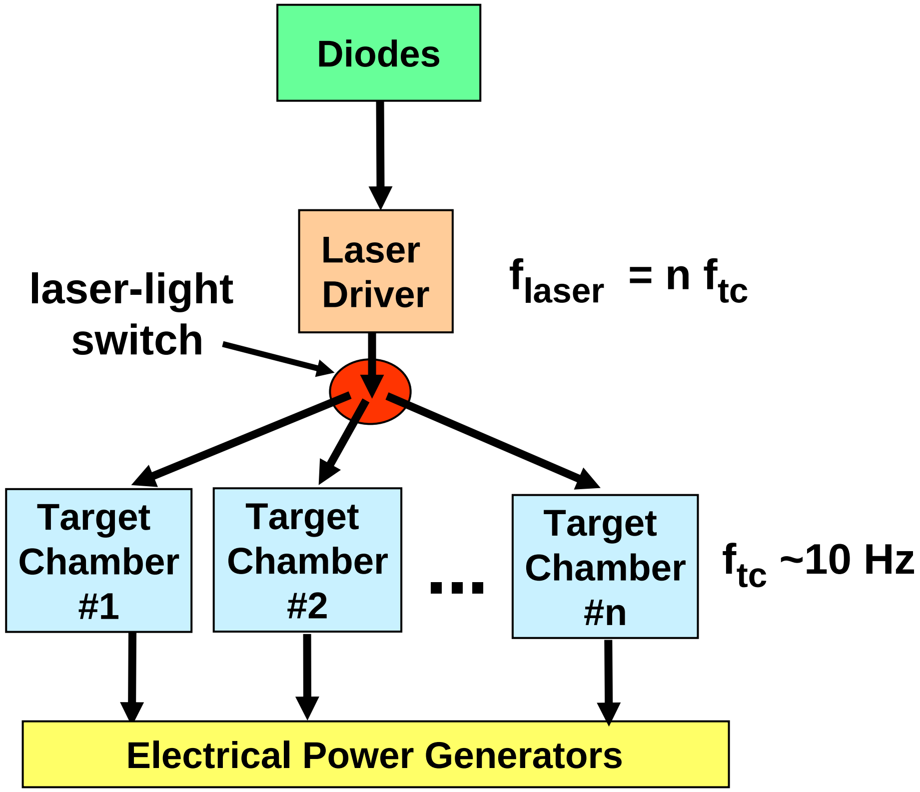
Current architecture



- Repetition rates are limited to ~ 5 – 10 Hz by target and target-chamber issues
  - clearance time for target debris
  - target injection rates
  - cost per target

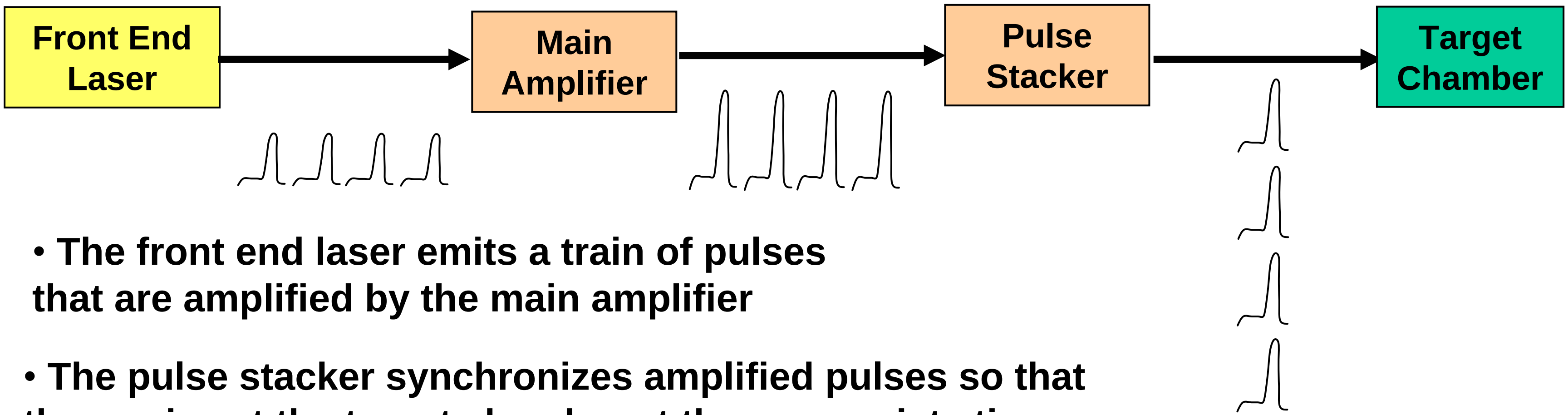
- DPSSLs could operate at higher repetition rates and duty cycles, depending on their design
  - diodes could have much greater duty cycles than current values of ~ 0.01
  - driver lasers could operate at greater repetition rates if the thermal shock parameter of the gain medium is high enough

Using the laser to pump more than one target chamber increases duty cycles for laser components



- An entire laser beamline is replaced by a single switch
- Driver cost is spread over several target chambers – high leverage
- Building the laser-light switch is the challenge
- Concepts include:
  - Rotating mechanical switch
  - High-average-power Pockels cell
- This is an old idea
- Cost of electricity is lowest when electrical power per target chamber is large and electrical power is multi-GW
- Selling multi-GW plants will be more difficult than selling ~ 1-GW plants

Pulse stacking also increases duty cycles for laser components



• The front end laser emits a train of pulses that are amplified by the main amplifier

• The pulse stacker synchronizes amplified pulses so that they arrive at the target chamber at the appropriate time

• There is high leverage for reducing overall costs since amplifier hardware counts scale as 1/# of pulses per amplifier

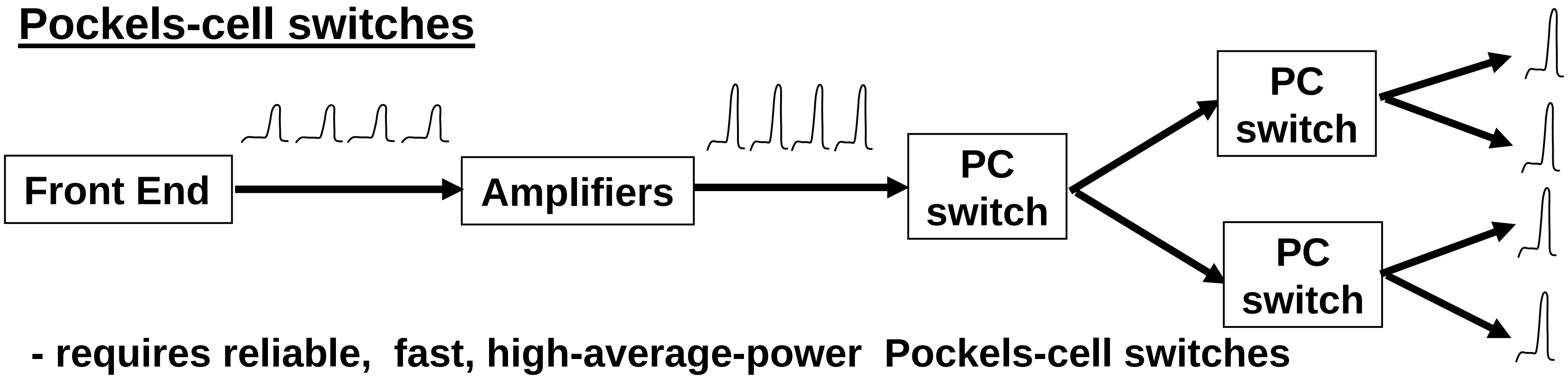
• Damage thresholds and average-power thermal loadings are issues

• There are several ways for separating pulses from each beamline and directing them along different pathways to the target

- Pockels-cell switches
- wavelength multiplexing
- counter-propagating beams
- angle multiplexing

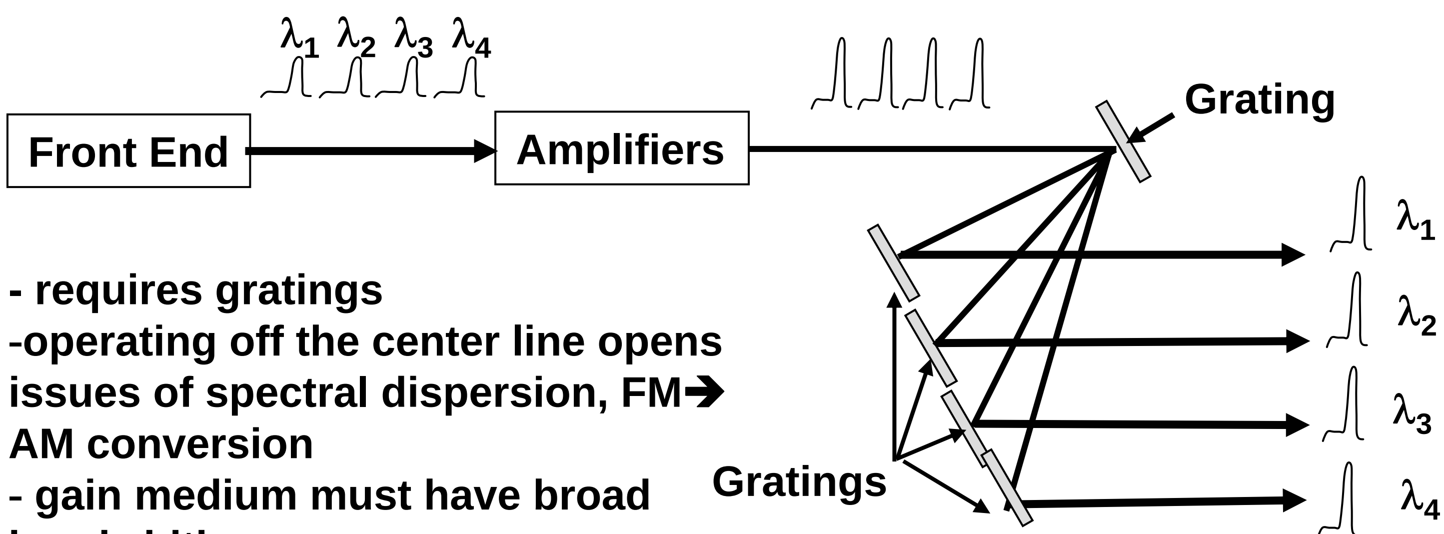
Four methods for separating pulses in a train have been considered

Pockels-cell switches



- requires reliable, fast, high-average-power Pockels-cell switches

Wavelength multiplexing

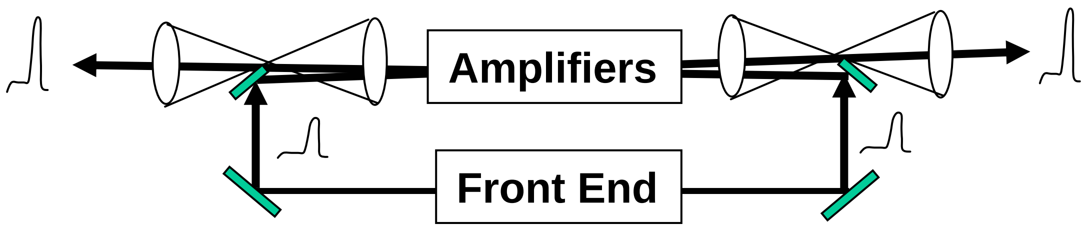


- requires gratings
- operating off the center line opens issues of spectral dispersion, FM→ AM conversion
- gain medium must have broad bandwidth

continued on next slide →

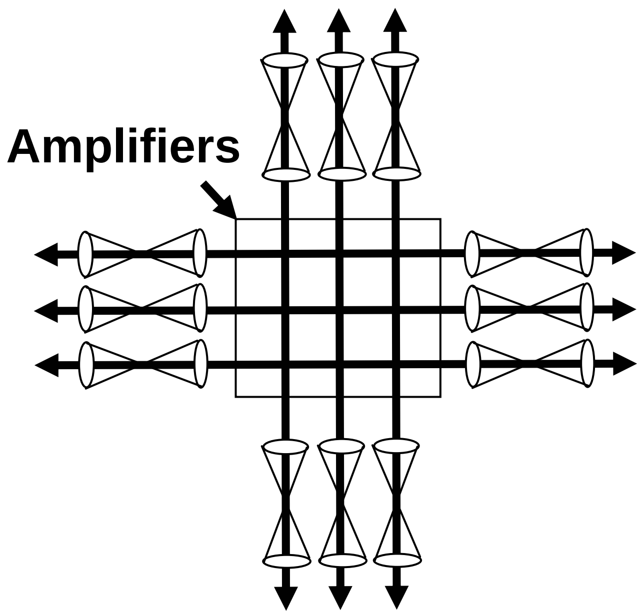
Four methods for separating pulses in a train have been considered (2)

Counter-propagating pulses



- pulse overlap can be avoided
- only two pulses can be generated this way per beamline

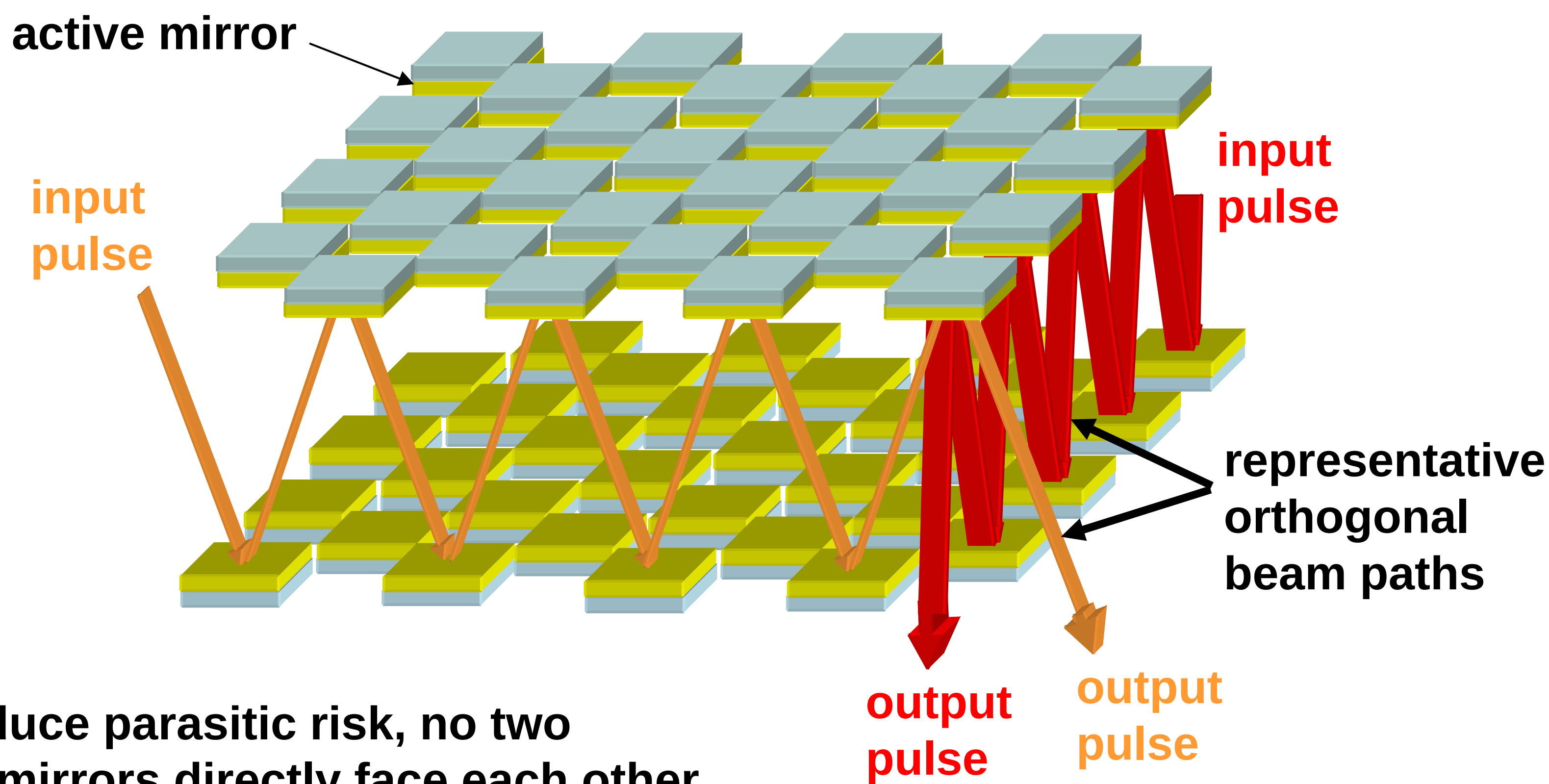
Angle-multiplexing (large-angle version)



- gain elements must be arranged in arrays to allow propagation in different directions

- this method can be combined with the other methods above to increase the number of pulses produced by the array

Two-dimensional active-mirror arrays allow beams to propagate in two orthogonal directions through the amplifier

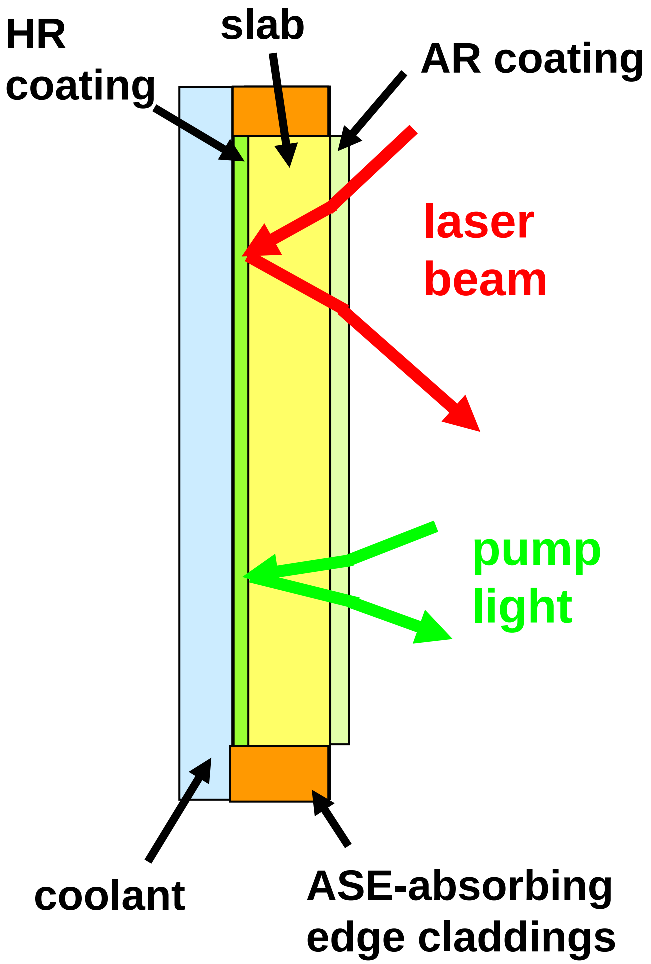


- to reduce parasitic risk, no two active mirrors directly face each other

- beams can be multi-passed rather than single passed

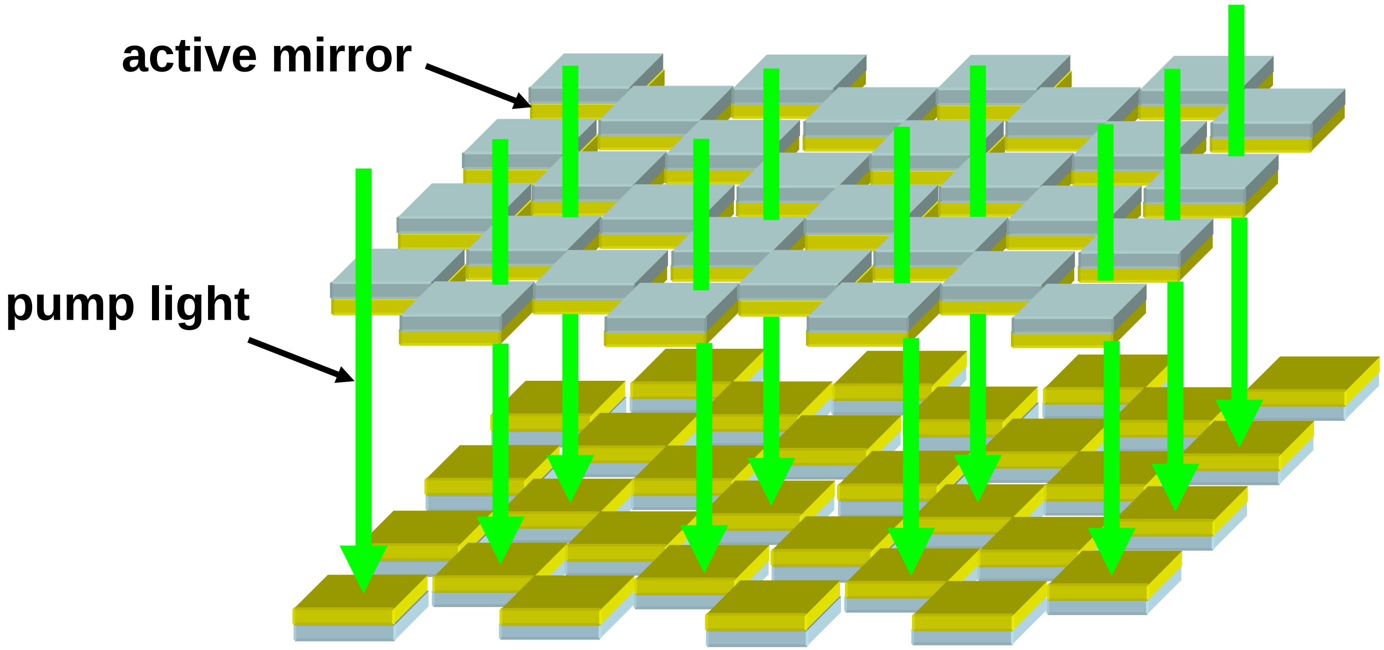
- each beam path can support multiple pulses by using Pockels-cell switches, wavelength multiplexing, or counter-propagating beams

Active mirrors amplify laser pulses that make two passes through the laser slab



- The main laser beam is transmitted through a front-surface AR coating and is reflected by a rear-surface mirror
  - -operation is inherently double-pass
- Back surface is liquid cooled
- Pump light is incident is also incident from the front surface and makes two passes through the laser slab
- Liquid cooling has advantages relative to gas cooling
  - less costly hardware
  - less power consumption
- The laser slab must have high thermal conductivity for low thermal distortion and high repetition rates

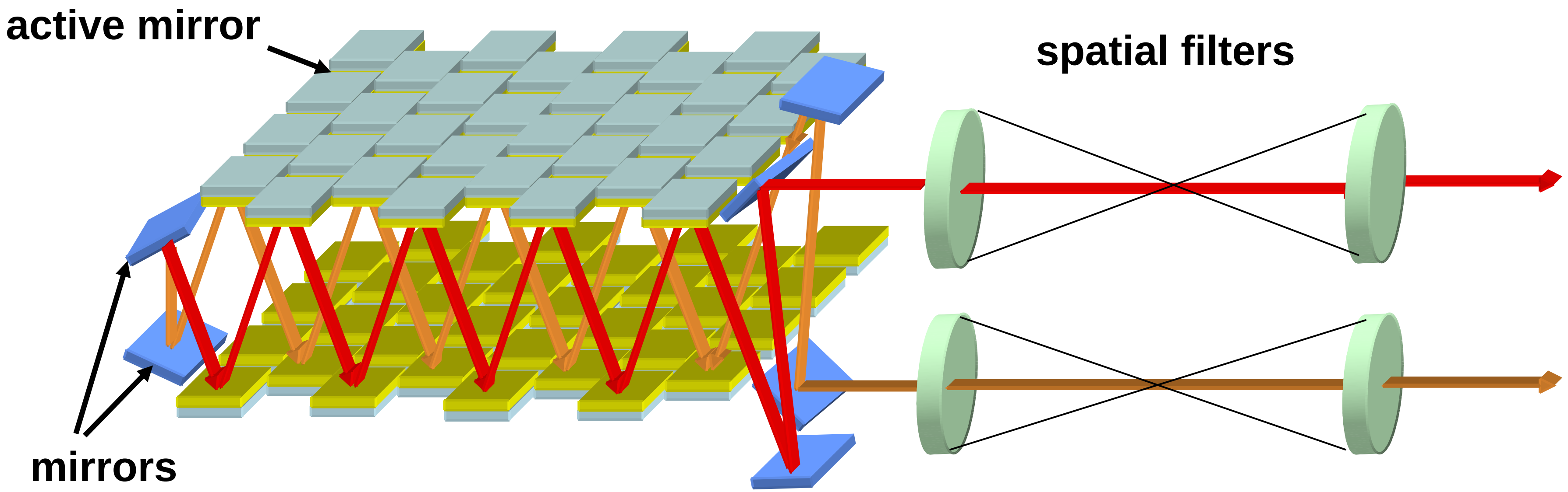
Pump light for each array is delivered through openings in the facing array



- In the example above, pump light propagates from above and pumps the lower array, but pump light propagating from below is also needed to pump the upper array

- It is also possible to pump the rear surfaces of the active mirrors, rather than the front surfaces

Amplifier cavities can be set up around the active-mirror arrays by using mirrors and spatial filters



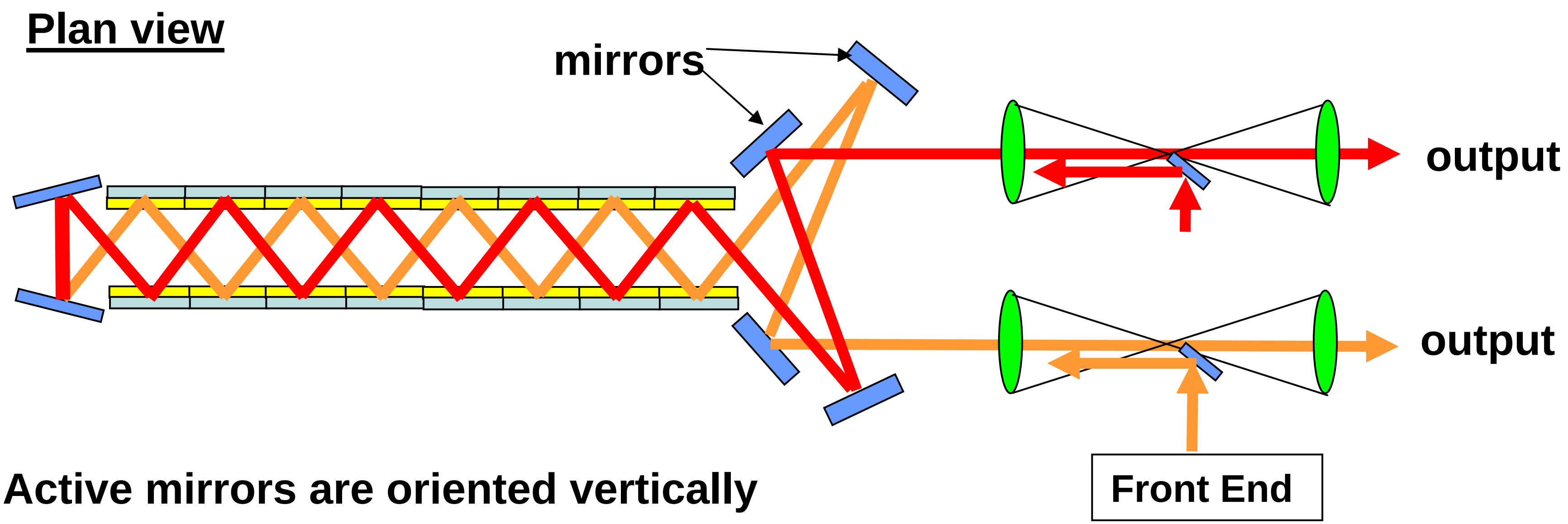
- in this example, the beam encounters 16 active mirrors, 8 per pass

- two rows of active mirrors are used – the nearest row (red beam) and the adjacent row (brown beam)

- beam rotation by the mirrors must be taken into account

- folding the cavity allows all spatial filters to be put on one side

Two counter-propagating beams might be generated



- Active mirrors are oriented vertically

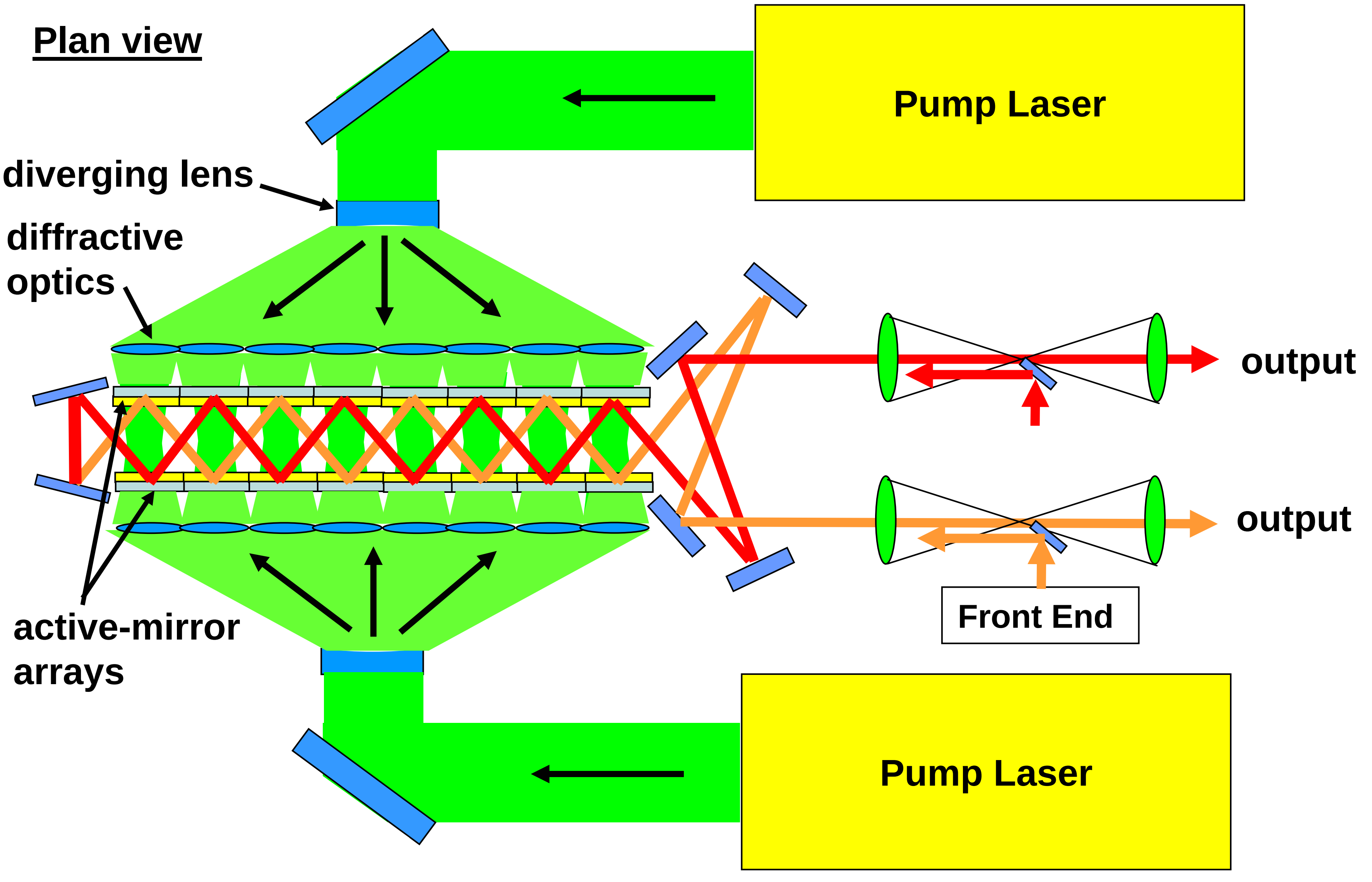
- Using counter-propagating beams doubles the number of pulses generated per slab

- Counter-propagating beams should be timed to avoid pulse overlap

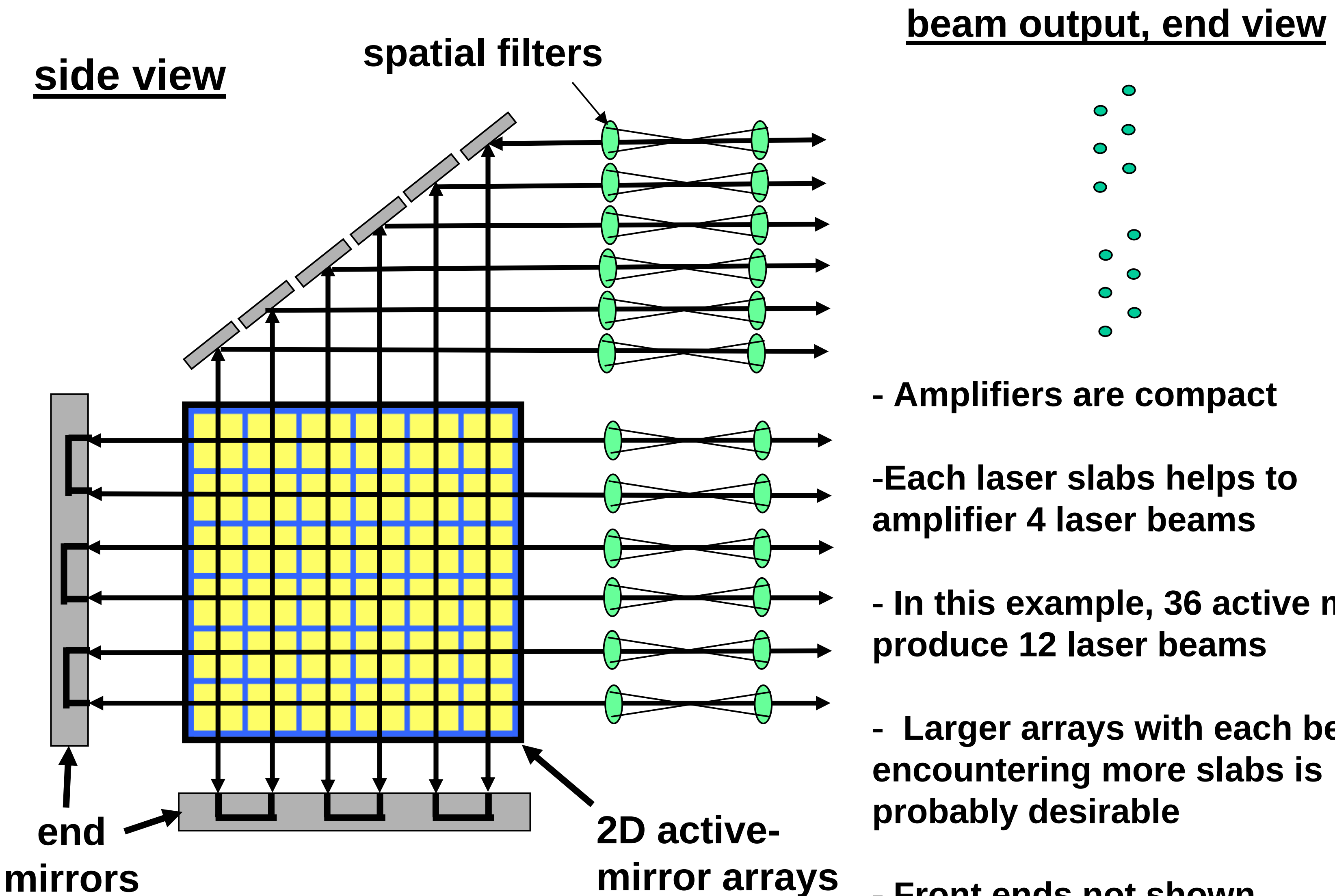
- Output pulses must have different path lengths to the target, so that they arrive at the same time

- Active mirrors need to be re-pumped between pulses to maintain gain

Pump light is delivered through the sides of the active-mirror arrays



A single compact amplifier array using angle multiplexing and counter-propagating pulses can produce many output beams



- Amplifiers are compact

-Each laser slabs helps to amplifier 4 laser beams

- In this example, 36 active mirrors produce 12 laser beams

- Larger arrays with each beam encountering more slabs is probably desirable

- Front ends not shown

Summary

• DPSSL drivers that are based on current concepts are too expensive for economically-competitive IFE power plants

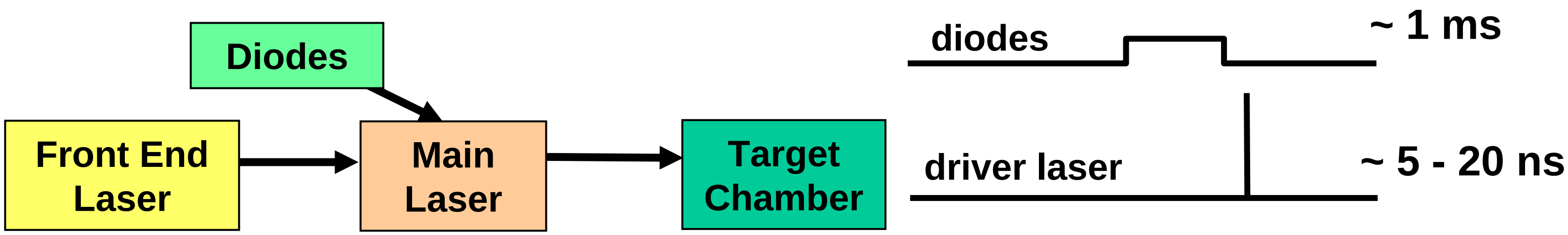
• Pulse stacking holds promise for reducing DPSSL driver costs

• A laser-pumped laser architecture has advantages

• We plan to evaluate and develop these concepts

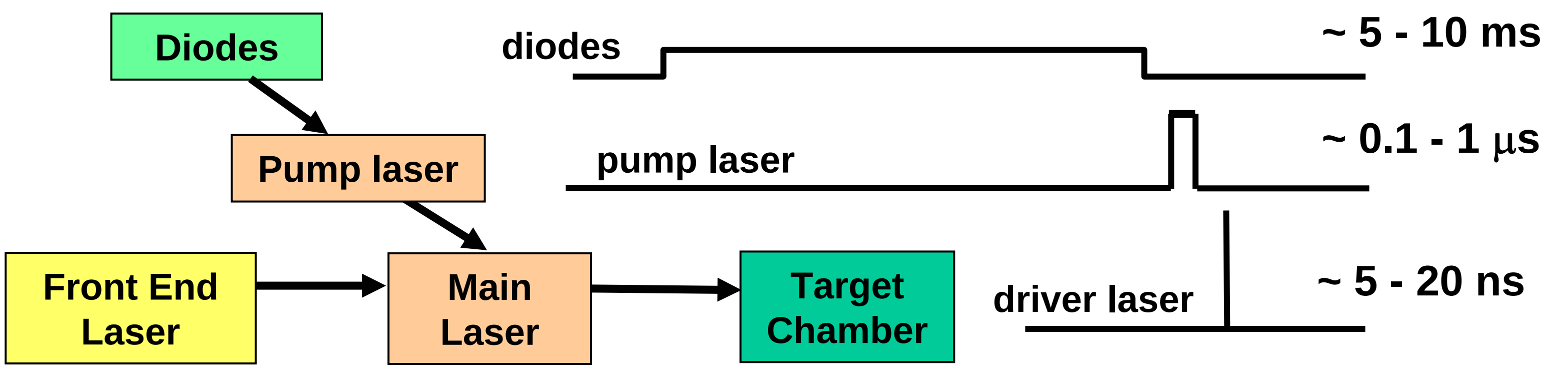
A laser-pumped-laser architecture allows gain media with longer storage lifetimes to be used

Conventional system



- Storage lifetime is limited by the need to extract stored energy efficiently in short pulses without damage

Laser-pumped-laser concept



- Diodes pump a "pump laser", which has a very long storage lifetime
- Stored energy can be extracted safely and efficiently at high fluence in ~μs pulses
- Pump laser pumps the main driver laser
- Number of diodes can be reduced by ~ ratio of storage lifetimes, $\tau_{\text{pump laser}} / \tau_{\text{driver laser}}$

A candidate laser-pumped-laser system uses a diode-pumped Yb:SrF_2 laser to pump a Ti:sapphire laser

diodes → Yb:SrF2 laser

τ_{store} ~ 10 ms

ϕ_{sat} ~ 100 J/cm²

→ Harmonic Converter → Ti:S laser

Front End Laser → Ti:S laser

τ_{store} ~ 3 μs

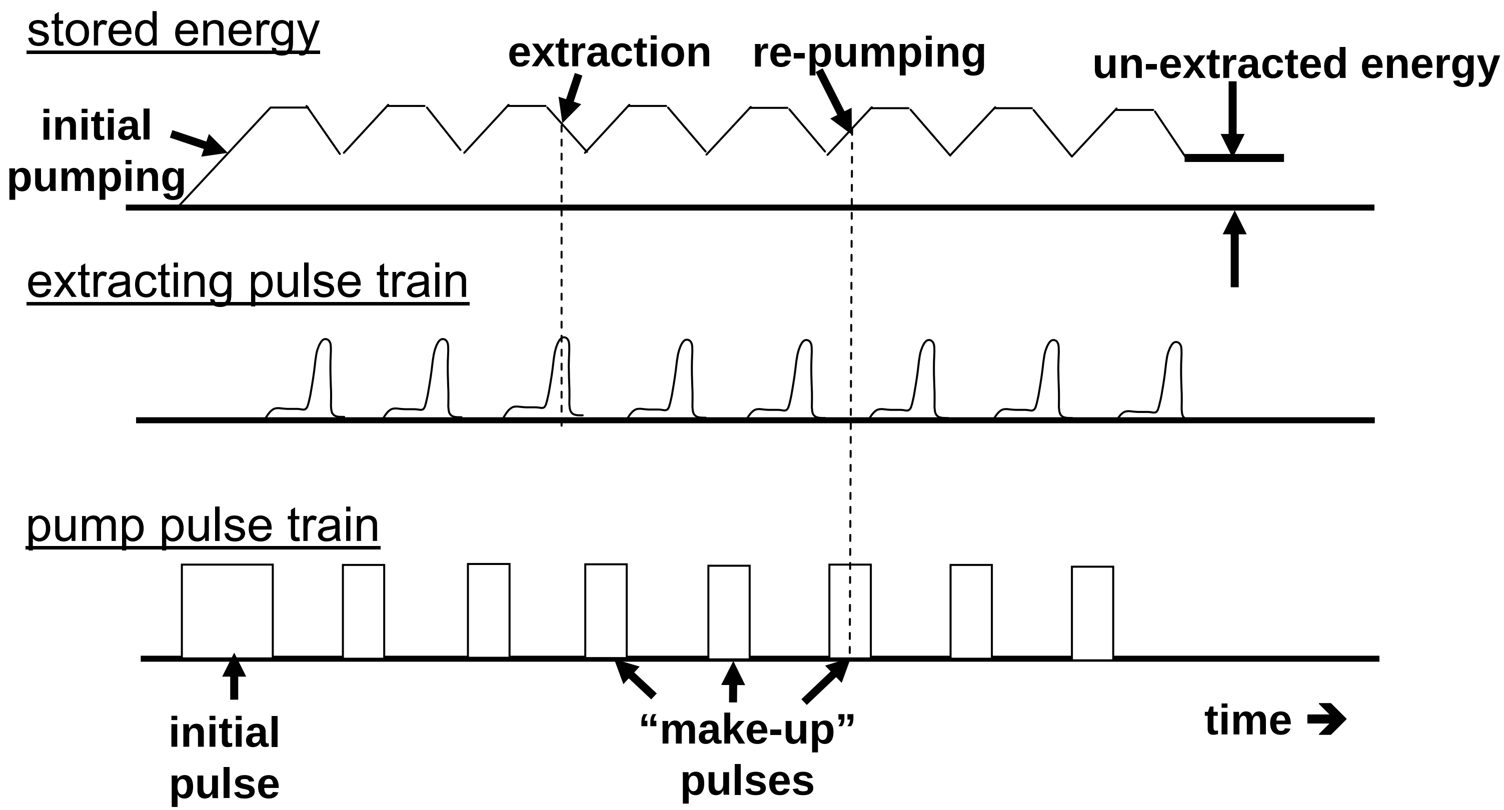
ϕ_{sat} ~ 1 J/cm²

→ Harmonic Converter → Target Chamber

- Uses only 10-20% as many diodes as a conventional Yb:S-FAP or Yb:YAG system
- Efficiency is the main issue
  - wall-plug efficiency of ~10% seems feasible but will require development (~13% for a conventional Yb:S-FAP system)
- Energy is extracted using > 100 ns – long pulses, or several pulses, to avoid damage
- Prospects are good for developing
  ~ 18-cm-diameter crystals
  ~ 40-cm x 80-cm ceramics

- ~10-cm-diameter Ti:S crystals are available now but yield is low
- Market forces are pushing vendors toward larger crystals
- Larger slabs seem desirable and would require development

Using slabs to amplify multiple pulses can increase extraction efficiency



- Slabs are re-pumped by "make-up" pulses after the passage of each extracting pulse
- Make-up pulses need only replace extracted energy – an efficiency advantage
- Loss due to incomplete extraction is only the energy left after the last extracting pulse
- High extraction efficiency can be achieved with less square pulse distortion
- Pump-pulse train could be replaced with a continuous pulse

Summary

• DPSSL drivers based on current concepts are too expensive for economically-competitive IFE power plants

• Pulse stacking holds promise for reducing DPSSL driver costs

- laser hardware produces multiple pulses, so less laser hardware is needed
- an implementation of pulse stacking uses orthogonal beams traversing two-dimensional arrays of active mirrors and counter-propagating beams

• A laser-pumped laser architecture has advantages

- by re-pumping amplifiers between pulses, amplifiers can produce pulse trains having greater energy
- by choosing for the pump laser a gain medium that has a long storage lifetime, the number of diodes can be reduced (by a factor of ~ 10 wrt Nd:YAG)

• We plan to evaluate and develop these concepts

- detailed modeling and evaluation of possible materials will be essential